APPLICATION OF PULSE VELOCITY TESTS TO SEVERAL LABORATORY STUDIES OF MATERIALS

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by
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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

TECHNICAL PAPER

APPLICATION OF PULSE VELOCITY TESTS
TO SEVERAL LABORATORY STUDIES OF MATERIALS

TO: K. B. Woods, Director
Joint Highway Research Project

December 18, 1957

FROM: H. L. Michael, Assistant Director

File: 9-2
Project C-36-25

Attached is a technical paper entitled, "Application of Pulse Velocity Tests to Several Laboratory Studies of Materials." This paper has been authored by Professors Woods and McLaughlin. It will be presented at the 37th Annual Meeting of the Highway Research Board in Washington in January, 1958.

The paper is a summary of three published papers and many unpublished reports on this subject that have previously been presented to the Advisory Board. It also illustrates the application of the soniscope or pulse velocity technique to a variety of situations.

The paper is presented for the record.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

HLM:hgb

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TECHNICAL PAPER

APPLICATION OF PULSE VELOCITY TESTS TO SEVERAL LABORATORY STUDIES OF MATERIALS

by

K. B. Woods, Director
and
J. F. McLaughlin, Research Engineer

Joint Highway Research Project
File: 9-2
Project C-36-25

Purdue University
Lafayette, Indiana

December 18, 1957

INTRODUCTION

In February, 1950 plans for the construction of a soniscope were prepared by E. A. Whitehurst, then a member of the staff of the Joint Highway Research Project of Purdue University, and were approved by the Advisory Board of that organization. Construction of the instrument followed and by September of that year the soniscope was available for testing. Upon its completion, Purdue University became the fifth organization known to own such a device, the others being the Hydro-Electric Power Commission of Ontario, the Portland Cement Association, the University of California, and Kansas State College.

In the years following, the soniscope was used in a variety of experimental investigations dealing with highway pavements and materials (1, 2, 3). It is the purpose of this paper to review and summarize the pertinent parts of several of these investigations and to illustrate the application of the soniscope or the pulse-velocity technique in a variety of situations.

This paper is based on three published papers and many unpublished reports which were written by present and former members of the staff of the Joint Highway Research Project, School of Civil Engineering, Purdue University. The authors wish to acknowledge the work of E. A. Whitehurst, D. W. Lewis, G. M. Batchelder, and E. J. Yoder. These men conducted the investigations and reported the results which are herein summarized. References to the original publications by these authors appear at the end of this report.

MEASURING SETTING TIME OF CONCRETE[1]

There is an obvious need for a method of determining the setting time of concrete. A needle penetration test such as is applied to neat-cement paste cannot be readily adapted to concrete because of the large range in particle size of the ingredients.

There have been several references in the literature concerning the possibility of measuring changes in the condition of green concrete through the use of a dynamic method of test. Specific mention has been made of measuring the velocity with which an energy pulse travels through the concrete. Jones (4), in 1949, reported making such tests on laboratory specimens using equipment built in the Road Research Laboratory, England. He stated, however, that below ages of 10 hours, considerable difficulty was experienced in obtaining an adequate signal through the concrete. This study by Jones and an additional study made by Arndt (5) suggested the study.

The purpose of this study was to investigate the possibility of determining the setting time of concrete by measurement of pulse velocities through the still plastic material. No effort was made to investigate the several variables which influence the time of setting of concrete. In so far as possible, these variables were minimized except where necessary to provide sufficient range in setting times to permit a satisfactory evaluation of the proposed test method.

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[1] Abstracted from reference 1

In order to introduce into the study some element which would cause the time of set of the concretes to vary, preferably in some predetermined manner and still keep all mixes as uniform as possible, it was decided that the mix design and method of handling should be kept constant and one of the constituents of the mix should be varied. Since various portland cements conforming to ASTM types I, II, III, and IV could be procured, the type of cement used was, in most cases, the only variable between batches.

Most of the concrete mixtures contained 6 bags of cement per cubic yard of concrete and were designed to have a nominal water - cement ratio of 0.40 by weight. The use of very stiff (0 to 3/8 in. slump) mixes permitted the early removal of the end plates of the specimen molds, thus obtaining access to the ends of the beams for testing purposes. Two mixes of a somewhat wetter consistency (6-1/2 and 2-1/2 in. slump) were also included.

Specimens were cast into 4 by 4 by 16-in. beams. Nine beams were cast from each 1.5-cu. ft. batch; three triple-section molds were employed. Specimens were molded, generally, in accordance with the ASTM requirements for the molding of laboratory specimens. Because of the unusual stiffness of the plastic concrete, extensive rodding was required. The top surfaces of the beams were finished with a dampened wooden float, an operation which was rather difficult. Despite considerable effort to achieve well-compacted specimens, some honeycombing was noted in most cases.

The forms used were so constructed that single plates at each end served as the end plates for all three beams. Shortly after the floating of the specimen surfaces was completed, these end plates were removed.

Pulse velocity tests were begun on the beams as soon as possible after the removal of the end plates. Initial velocity tests were made on the specimens in the first mold from 2 to 4 hr. after the concrete was mixed, depending upon the type of cement used. Earlier tests were attempted but were found to be unsatisfactory. Once a satisfactory test was accomplished, the beams were tested repeatedly, usually at intervals of 1/2 hr.

It had been suggested that the vibrations passed through the specimen in testing, though of a minute nature, might have some material effect upon the concrete. To check this hypothesis, only the specimens cast in the first mold were tested throughout the entire setting period. Those in the second mold were subjected to their first velocity tests approximately 3 hr. after those in the first mold, after the setting process was well under way. Tests were not begun on the beams in the third mold until it was felt that final set had occurred. Only a few tests were made on these specimens.

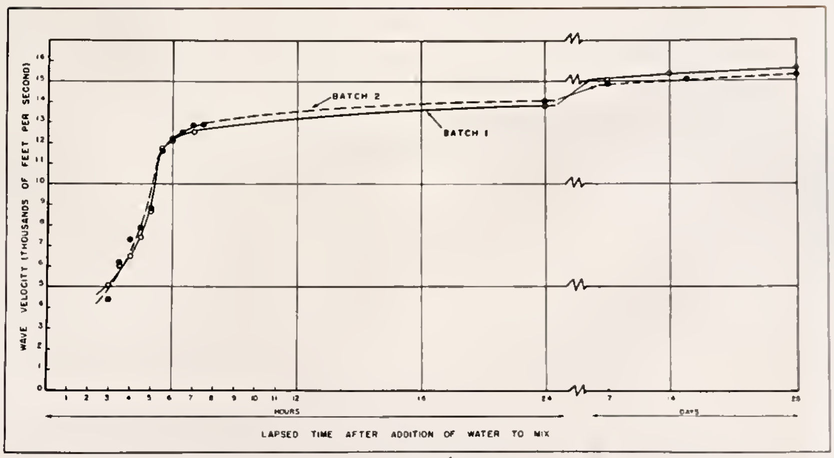
The half-hour velocity tests were continued until the specimens were 8 to 9 hr. old and appeared to have reached final set. The beams were then allowed to remain in the forms over night. On the following morning, when the concrete was approximately 24-hr. old, velocity tests were made on all nine of the specimens, the forms were stripped, and the beams were moved to the moist room. Additional velocity tests were made when the specimens reached ages of 7, 14 and 28 days.

Discussion of Results

In all cases it was found that the pulse velocity through the specimens increased at a rapid rate during the first few hours after the concrete was mixed. Figures 1 and 2 show the results of tests on mixes containing Types I and II cements, respectively. The results from Types III and IV were similar.

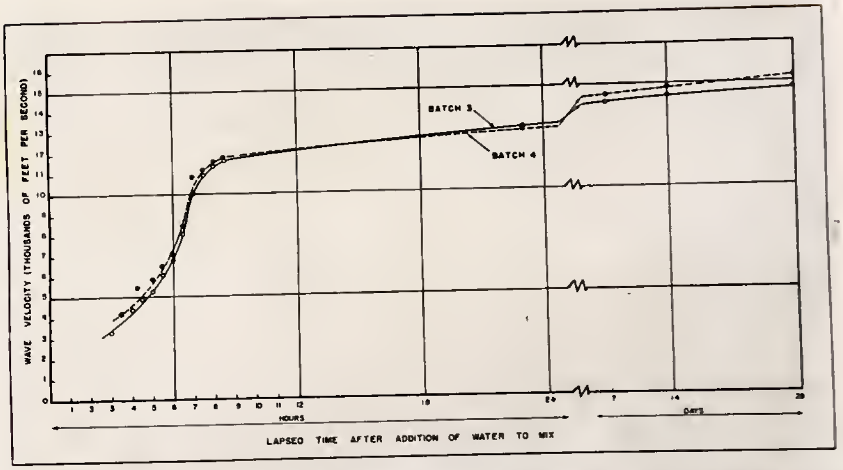
Each point on the graphs represents the average of test values for the three beams cast in the first mold. It may be noted that velocity when first measured was in the range of 3000 to 6000 feet per second. From this initial value it increased at an accelerating rate for several hours. At the end of some period of time, the rate of change in velocity decreased sharply during a relatively brief interval. Velocities then continued to increase at a slow rate throughout the duration of the tests. Only very small differences were observed between the three companion specimens in any given mold.

It seems desirable, especially for the evaluation of acceleration of retarding admixtures, to designate a specific time as the time of set. From a study of the data it appeared that the time which could be most consistently reproduced was that designated by the intersection of lines drawn tangent to the curve before and after the interval during which the rate of change in velocity decreased sharply. Figure 3 shows a comparison of results of velocity tests on concretes made from the four cements used in this study. The tangents have been drawn to indicate the time of set. A comparison of the



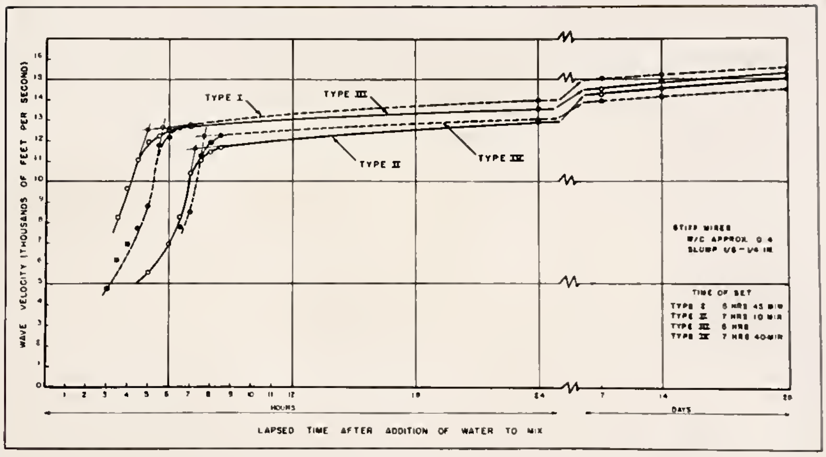
[redacted] - AVERAGE WAVE VELOCITIES THROUGH CONCRETE MADE FROM TYPE I CEMENT

Figure 1



AVERAGE WAVE VELOCITIES THROUGH CONCRETE MADE FROM TYPE II CEMENT

Figure 2



COMPARISON OF WAVE VELOCITIES THROUGH CONCRETES MADE FROM TYPES I, II, III, & IV CEMENTS, STIFF MIXES

Figure 3

setting times so determined with the setting time of the cement alone, as determined by the Gillmore needle, is shown in Table I.

Some additional tests were made on concretes having a nominal water-cement ratio of 0.5 and which were considerably wetter than those so far discussed. It was found that results similar to those obtained with the stiff mixes were obtained.

Conclusions

From the results of the tests, it was concluded, at least for specimens of laboratory size, that the setting time of concrete may be determined by observing the rate of change of the velocity with which small vibrations are propagated through the specimen. Time of set is taken as the time at which this rate of change decreases suddenly. If the velocity is measured periodically and plotted versus elapsed-time-after-mixing, this time may be determined by locating the point of intersection of tangents drawn to the curve immediately prior to and after the period during which the decrease occurs.

The soniscope appears to be a suitable instrument for measuring the desired velocities.

The test is rather difficult to perform because of the very weak signals received during the setting period. With a little experience, however, an operator is able to achieve reliable and reproducible results. It should be noted that the increase in velocity is generally so great immediately prior to the setting of the concrete that the change could scarcely be missed, even if the accuracy of measurement were poor.

The method is probably no more precise than are the needle

TABLE I

COMPARISON OF SETTING TIME OF
CONCRETE AND CEMENT

Type Cement	Time of Set	
	Concrete	Cement
Type I	5 hr, 45 min	5 hr, 45 min
Type II	7 hr, 10 min	6 hr, 50 min
Type III	5 hr.	4 hr, 15 min
Type IV	7 hr, 40 min	8 hr.

tests for setting time of cement, since the phenomenon of final set is not an instantaneous process. The method does, however, provide a means of quantitatively evaluating the setting time of concrete.

COMPARISON OF DYNAMIC METHODS OF TESTING CONCRETES SUBJECTED TO FREEZING AND THAWING[2]

In recent years, dynamic techniques have been widely used in concrete testing, particularly in connection with durability studies. Dynamic testing techniques are divided into two general methods, one based upon determination of the fundamental resonant frequency of vibration of a specimen and the other upon measurement of the velocity of a compressional wave through the material. Many investigations of these techniques and their application to concrete have been made in the past. Correlations of changes in the dynamic modulus of elasticity with the deterioration of concrete subjected to freezing and thawing and with changes in the flexural strength have been made by several investigators. As a result, the test is widely used in durability testing of concrete. The method is restricted to tests on laboratory specimens with uniform cross-sections.

Investigations using velocity measurements, which are not affected by specimen shape and can be used in the field, apparently were started by Long and Kurtz (6). Later reports by Long, Kurtz, and Sandenaw (7) and West (8, 9) gave test results of a similar nature involving measurement of the transit time of a single impact pulse through the concrete between two pickups.

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[2] Abstracted from reference 2

This paper reports the results of laboratory tests to compare the resonant frequency and velocity test techniques for determining the deterioration of laboratory specimens of concrete subjected to freezing and thawing, and to compare the actual moduli of elasticity values computed from the results obtained by the two test methods. Theoretically, the same results should be obtained from tests on the same specimens by the two methods.

Two series of tests were conducted. The first, designated as series A, involved transverse resonant frequency and velocity tests on three concretes (two mixes of each). Comparisons of test results were made on the basis of changes in velocity squared and in the dynamic modulus of elasticity calculated from the transverse frequency during freezing and thawing. In series B, tests were run on two concretes (one mix of each). Longitudinal, transverse, and torsional frequencies were determined and velocities measured in this series. Values of the modulus of rigidity and Poisson's ratio were obtained, and moduli of elasticity were computed from the longitudinal and transverse frequencies and from the velocities.

All specimens were cured for 28 days completely immersed in water at 70F, except those from mix 1, series B, which were cured only 21 days. At the end of the curing period, three beams from each mix in series A and eleven from each mix in series B were subjected to alternate freezing and thawing. The cycle consisted of a 16-hr freezing period and an 8-hr thawing period. Freezing was done in air at -18F in a walk-in freezer; thawing was in running tap water at 55F. Resonant frequency and velocity tests was made periodically during freezing and thawing. At the end of the testing, beams were broken in flexure.

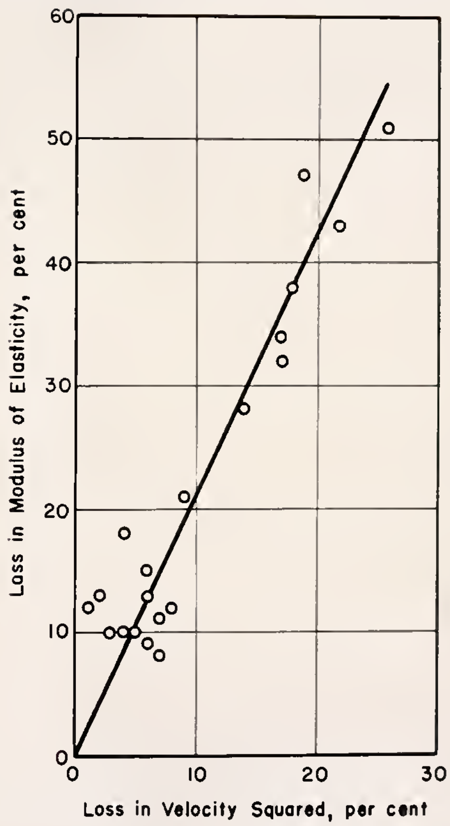
Series A: During the freezing-and-thawing tests on series A specimens, periodic measurements were made of velocity and transverse resonant frequency on each specimen. Modulus of elasticity values were calculated from the transverse frequencies, using the equations given in ASTM C 215-52T, Tentative Method of Test for Fundamental Transverse and Torsional Frequencies of Concrete Specimens. Poisson's ratio was assumed to have a value of 1/6.

Series B: More complete dynamic tests were conducted on the specimens in series B, where longitudinal, transverse, and torsional resonant frequencies and velocities were measured. Modulus of elasticity, modulus of rigidity, and Poisson's ratio values were determined for each test.

Discussion of Results

Series A: Since no attempt was made in this series of tests to determine the value of Poisson's ratio, modulus of elasticity values were not calculated from the velocity measurements. Instead, the results of the tests were compared on the basis of the relative changes in dynamic modulus of elasticity (based on transverse frequency) and in velocity squared. It may be shown that the square of the velocity is directly proportional to the modulus of elasticity. Therefore, changes in velocity squared, calculated as percentages of the original value, would be the same as the percentage changes in modulus of elasticity. This assumes that Poisson's ratio, whatever its value may be, remains constant during the freezing-and-thawing cycles.

The results of the tests in series A are shown in Fig. 4, where changes in the transverse modulus of elasticity are plotted against



Loss in Modulus of Elasticity, per cent
0
10
20
30
40
50
60
0
10
20
30
Loss in Velocity Squared, per cent

Figure 4

changes in the velocity squared. Each plotted point shows the average value obtained from tests on six specimens, three from each of two mixes, after varying numbers of cycles of freezing and thawing.

The average line for the data shown in Fig. 4 does not indicate the equal changes in modulus of elasticity and in velocity squared that had been expected. Instead, the percentage change in modulus of elasticity is approximately twice as great as the change in velocity squared. The data, then, show that velocity measurements were only about one half as sensitive as transverse resonant frequency tests as a measure of the deterioration of these concretes during freezing and thawing.

Original velocity measurements on these specimens showed a range of values from 14,700 to 15,860 ft. per second. Velocities during the freezing-and-thawing tests were never less than 12,000 ft. per second, although decreases in dynamic modulus of elasticity ranged up to 50 percent.

No reason was apparent for the lack of correlation of the values obtained in this test series. Among the possible explanations considered were:

1. Poisson's ratio may not remain constant as deterioration progresses. If Poisson's ratio increased with deterioration of the concrete, the effect would be to decrease the modulus of elasticity value calculated from the velocity, thus making changes from the original value greater.

2. The concrete may not be sufficiently homogeneous, especially along the "line path" over which velocity tests are conducted, for

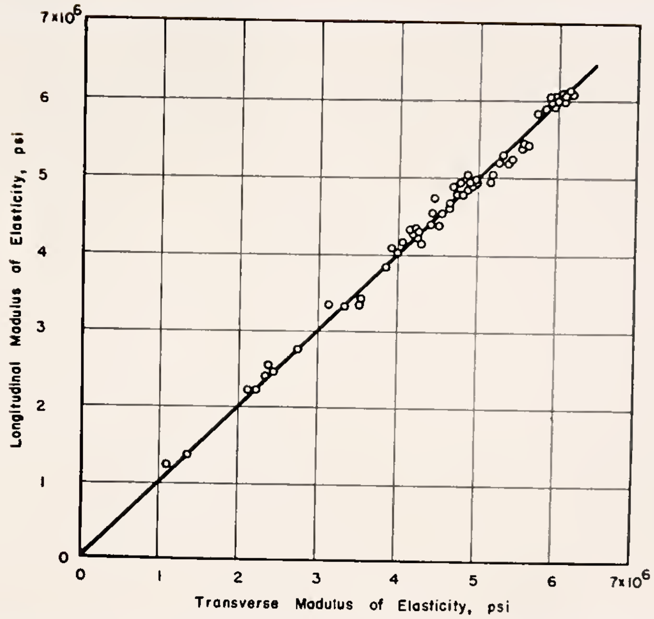
the equations relating modulus of elasticity to velocity to be applicable. In this case, correlation of the modulus of elasticity values from resonant frequency and velocity tests would be poor even in initial tests before any weathering cycles were started.

3. The possibility exists that the resonant frequency values are dependent upon the "average" condition of the specimen, while the velocity is measured along a single line. The compressional waves used in the velocity test would tend to travel through the soundest material in the specimen, and the results would not reflect the "average" condition of the concrete.

Series B: The tests conducted in series B were designed to determine the changes, if any, in Poisson's ratio during freezing and thawing and to compare actual values of the modulus of elasticity calculated from the velocity with the values obtained from the resonant frequencies.

Comparison of Moduli of Elasticity from Longitudinal and Transverse Frequencies. Only the transverse frequencies are ordinarily obtained in routine dynamic testing. Therefore, it was of interest to compare the modulus of elasticity values so obtained with those calculated from the fundamental longitudinal frequencies. These values for mix 1 are plotted in Fig. 5. Each plotted point represents one test on a single specimen. Excellent correlation is shown, the values lying on or very close to the line of equal values drawn on the graph. Values obtained for mix 2 showed a similarly close correlation.

Comparison of Moduli of Elasticity from Transverse Frequency and Velocity. In Fig. 6 data from the same specimens in mix 1, showing



7x10^6
6
5
4
3
2
1
0
Longitudinal Modulus of Elasticity, psi
0
1
2
3
4
5
6
7x10^6
Transverse Modulus of Elasticity, psi

Figure 5

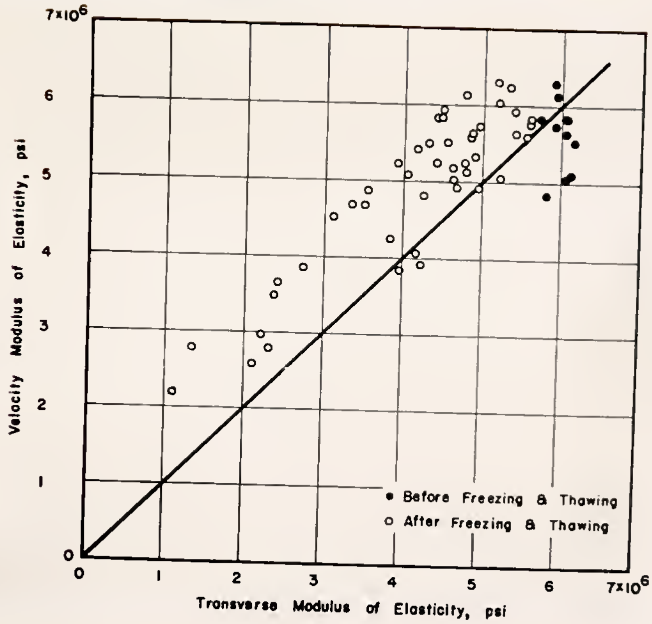

7x10^6
6
5
4
3
2
1
0
Velocity Modulus of Elasticity, psi
0
1
2
3
4
5
6
7x10^6
Transverse Modulus of Elasticity, psi
• Before Freezing & Thawing
o After Freezing & Thawing

Figure 6

the relationship of the moduli of elasticity calculated from transverse frequency and velocity, are plotted. As in Fig. 5 the curve shown is the theoretical line of equal values. It is readily apparent that the theoretical relationship does not hold, even though Poisson's ratio was determined for each test and was used in calculating the moduli of elasticity values. There is a definite general trend for the values computed from velocity measurements to be considerably higher than those computed from transverse frequency. It is significant, however, that a somewhat better correlation is shown for the original values - that is, those measured before freezing-and-thawing tests were started. Actually, these original values calculated from velocity tend to be lower than those from transverse frequency. After freezing and thawing, the reserve is true. This shows the same trend previously noted in test series A; that is, the change in modulus of elasticity calculated from velocity undergoes less change as the concrete deteriorates than does the value obtained from resonant frequency.

In mix 2, all values of modulus of elasticity were closely grouped, with little deterioration taking place. The initial values for the eleven specimens are shown in Table II. The values computed from velocity range from 8 percent higher to 18 percent lower than those from transverse frequency. Changes in these values were, in general, small during freezing and thawing. The reasonably good correlation noted for the initial values seemed to hold for this concrete mix throughout the tests, probably because of the small changes that took place.

It should be noted that the equation which was used to convert velocity to dynamic modulus of elasticity is one that Long, Kurtz and

TABLE II

INITIAL MODULUS OF ELASTICITY
VALUES, SERIES B, MIX 2

Beam	Modulus of Elasticity, psi		Percent Difference
	Transverse	Velocity	
No. 1	4.77×10^6	5.16×10^6	+8
No. 2	4.66	4.82	+3
No. 3	4.84	4.20	-13
No. 4	5.04	4.11	-18
No. 5	4.51	4.12	-9
No. 6	4.53	4.22	-7
No. 7	4.65	4.25	-7
No. 8	4.49	4.30	-4
No. 9	4.77	5.16	+8
No. 10	4.93	4.98	+1
No. 11	4.99	4.97	0
Average	4.74	4.57	-3.6

Sandenaw (7) recommended for mass concrete but which Leslie and Cheesman (10) recommended for all concrete, including laboratory specimens. This equation is:

$$E = \frac{V^2 \rho (1 + \mu)(1 - 2\mu)}{(1 - \mu)}$$

where:

E = modulus of elasticity

V = compressional wave velocity

ρ = density of concrete

μ = Poisson's ratio

<u>Changes in Velocity Squared and Dynamic Modulus of Elasticity Calculated from Velocity.</u> The changes in velocity squared and in modulus of elasticity calculated from velocity, shown in Table III, do not correspond well with the changes in the other dynamic moduli. The tendency, although not so pronounced, is the same as that encountered in test series A. The losses in velocity squared are less than the losses in the moduli of elasticity calculated from resonant frequencies (a greater percentage of the original value is retained).

Mix 2 data, shown in Table IV, indicate a much closer correlation of changes in the velocity values with changes in the other dynamic moduli. Apparently the closeness of the correlation is affected by the amount of deterioration that takes place. In the case of mix 2, there is little choice between velocity squared and modulus of elasticity calculated from velocity. Velocity squared does, however, tend to be a little closer to the other values after 15 cycles

TABLE III

DYNAMIC TEST VALUES DURING
FREEZING AND THAWING, SERIES B,
SPECIMENS 1 AND 2, MIX 1.

Number of Cycles of Freezing and Thawing	Dynamic Moduli and Velocity Squared, per cent of Original Value					Poisson's Ratio
	Longitudinal Modulus of Elasticity	Transverse Modulus of Elasticity	Modulus of Rigidity	Velocity Squared	Velocity Modulus of Elasticity	
0	100	100	100	100	100	0.30
1	88	90	90	96	102	0.27
2	82	82	85	94	106	0.24
4	76	75	80	82	94	0.24
6	68	70	72	79	90	0.24
10	56	57	58	70	82	0.23
15	44	42	45	56	63	0.25
20	40	39	42	48	55	0.23
25	36	36	39	41	48	0.23
36	21	20	24	33	43	0.15

TABLE IV

DYNAMIC TEST VALUES DURING
FREEZING AND THAWING, SERIES B,
SPECIMENS 1 AND 2, MIX 2.

Number of Cycles of Freezing and Thawing	Dynamic Moduli and Velocity Squared, per cent of Original Value					Poisson's Ratio
	Longitudinal Modulus of Elasticity	Transverse Modulus of Elasticity	Modulus of Rigidity	Velocity Squared	Velocity Modulus of Elasticity	
0	100	100	100	100	100	0.29
1	94	92	94	96	92	0.30
2	92	92	93	98	95	0.29
4	93	93	94	97	96	0.28
6	91	92	93	95	94	0.28
10	91	91	91	95	97	0.27
15	92	92	92	91	91	0.28
20	93	92	92	92	90	0.29
25	94	92	92	90	86	0.30
35	95	93	92	91	86	0.30
50	94	93	92	87	85	0.31

of freezing and thawing.

The results obtained in these tests indicate no benefits from determining Poisson's ratio and calculating values of modulus of elasticity from velocity measurements. Instead, the velocity values themselves appear to be a better measure of concrete deterioration than do the modulus of elasticity values calculated from velocity. These results confirm the opinion expressed by Whitehurst (1) that velocity measurements should be used as such, without attempting to calculate the dynamic modulus of elasticity.

Actual velocity values obtained for the specimens in test series B (other data shown in Tables III and IV) varied from 15,470 ft. per second initially to 9920 ft. per second after weathering for mix 1; and from 14,200 to 13,350 ft. per second for mix 2.

Changes in Poisson's ratio. The data in Table III show a definite trend in the values of Poisson's ratio, which decreased markedly as deterioration of the concrete took place. It should be noted that the change is in the opposite direction from that required to improve the correlation of the dynamic moduli changes from resonant frequency and velocity measurements. The effect of the variation in Poisson's ratio is to cause differences in the relative changes in velocity squared and in modulus of elasticity calculated from velocity. The changes in Poisson's ratio cannot account for the discrepancies in results noted above in the series A tests.

The changes in the calculated values of Poisson's ratio are caused by the difference between the changes in longitudinal modulus of elasticity and in modulus of rigidity. Although the percentage difference in the changes in these values is quite small, it is consistant. The change in modulus of rigidity is slightly less than the change in modulus of elasticity, resulting in an apparent decrease in Poisson's ratio. Although the significance of this change is difficult to determine, it seems reasonable that actual measurements of Poisson's ratio would be superior to the use of assumed values for calculation of modulus of elasticity from velocity determinations. Use of the measured values, however, causes greater discrepancies between changes in the velocity and resonant frequency moduli than does the assumption of a constant Poisson's ratio during the weathering tests.

The values of Poisson's ratio for mix 2 (Table IV) remained relatively constant during the freezing-and-thawing cycles. It appears probable that this is due to the small amount of deterioration that took place in this concrete mix. Since no great changes took place in the other characteristics of the concrete, Poisson's ratio might be expected to undergo but little change.

Summary

1. In general, no benefit is derived from calculating modulus of elasticity values from velocity measurements. When the concrete undergoes extensive deterioration, the changes in velocity squared form a more accurate indication of concrete deterioration than does such a modulus of elasticity.

2. If the modulus of elasticity is calculated from velocity, the equation recommended by Leslie and Cheesman should be used. Although inaccurate for the deteriorated concrete tested, this equation results in better correlation with resonant frequency moduli than do the other equations that have been suggested for velocity modulus of elasticity.

3. Velocity measurements are less sensitive to deterioration than are resonant frequency determinations. Decreases in resonant frequency moduli may be twice as great as the decreases in velocity moduli as the concrete deteriorates.

4. Measurements of longitudinal, transverse, or torsional resonant frequencies are equally useful and sensitive in tracing the deterioration of concrete specimens.

5. Poisson's ratio showed a definite decrease in the nondurable concrete as the weathering cycles progressed. This change is responsible for the differences noted between changes in velocity squared and in the modulus of elasticity calculated from the velocity.

6. It appears probable that the lack of correlation between changes in resonant frequency and velocity moduli, when the concrete deteriorates, is due to failure of the velocity measurements to indicate the "average" condition of the specimen. The pulse path in the velocity measurements would probably be through the soundest concrete in the interior of the specimen, and the results would indicate only the condition of the best portion of the concrete. An "average" condition for the entire mass of concrete should be indicated by the resonant frequency tests in which the whole specimen is vibrated.

DURABILITY TESTS ON LIME-STABILIZED SOILS[3]

The purpose of this study was three-fold: First, to determine the durability characteristics of lime-soil mixtures as affected by such variables as soil texture, soil density, and quantity of lime; second, to determine the effect of moist curing on the unconfined compressive strength and durability of lime-soil mixtures; and third, to explore the suitability of dynamic testing techniques for evaluating the performance of such mixtures.

Three different soils were used in this investigation. Soil 2849 was a silty clay of Wisconsin glacial age, a calcareous drift soil typical of that overlying a large portion of the central states. Soil 2853 was an Illinoian drift soil. The third soil, 3068, was a pit-run gravel with all material larger than 1/4 in. discarded.

The effects of the several variables upon strength were evaluated by unconfined compression tests. Relative durability was determined by freezing-and-thawing and velocity tests. Curing times ranged from 1 to 36 weeks and the quantity of lime from 0 to 10 percent by weight. Some tests were made on specimens of varying density.

Specimens were molded in a split cylinder the size of the standard Proctor cylinder (1/30 cu. ft.). They were molded at optimum moisture content as determined by compaction tests. The quantities of lime used were 2, 5, and 10 percent by dry weight.

<u>Curing and Freeze-Thaw Testing.</u> After compaction each specimen was weighed and placed in a moist room to cure for periods of 1, 4, 8, 15, and 36 weeks. After the prescribed curing period, one of

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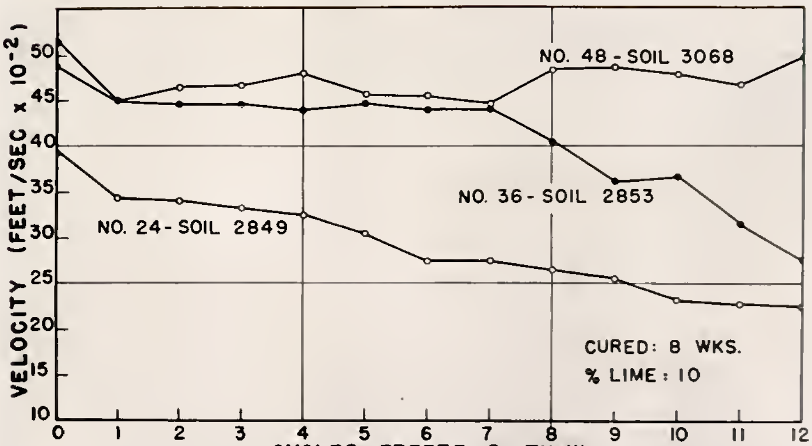
[3] Abstracted from reference 3

each pair of specimens was weighed, measured, and placed in a freezer for 24 hr. Air temperature in the freezer was maintained at 24F. This temperature was chosen since soil temperatures in the Midwest seldom go below this level.

Upon the completion of the 24-hr. freezing period, the specimens were removed from the freezer, reweighed, measured for volume change, and permitted to thaw. During the 24-hr. thawing period the specimens rested on porous stone disks with free water available for absorption through the disks. At the end of this period the specimens were again weighed and measured, tested with the soniscope, and returned to the freezer. Twelve of the above described cycles constituted the durability test for each specimen.

Durability Tests. Pulse velocities were measured through all specimens at the end of the curing period and after each cycle of thawing. Each specimen was tested until it failed or until 12 cycles of freezing and thawing were completed. The only exception occurred when the soniscope was overhauled for four days. During this period some specimens underwent two cycles of freezing and thawing without being tested. This is indicated on the attached data curves by dashed lines. These curves have been selected to show the influence of certain variables upon the durability of lime-soil specimens as evidenced by change in velocity.

Figure 7 shows the influence of soil type upon durability. Each of the specimens contained 10 percent lime and was cured for 8 weeks. A marked difference in performance may be noted. The specimen made from Soil 2849, the Wisconsin drift soil, shows continuous



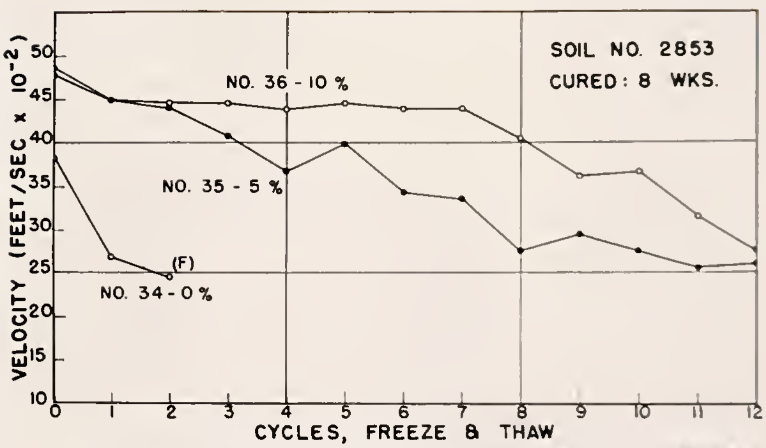
INFLUENCE OF SOIL TYPE ON DURABILITY

Figure 7

progressive distress, the velocity at the end of 12 cycles being only about 56 percent of the original velocity. The specimen made from Soil 2853, Illinoian drift, showed little distress until after seven cycles were completed. Deterioration then progressed until after 12 cycles, the velocity being only about 58 percent of its value after curing. The specimen made from Soil 3068, river terrace gravel, showed no significant loss in velocity after 12 cycles of freezing and thawing. This specimen was actually put through 30 cycles without suffering severe distress.

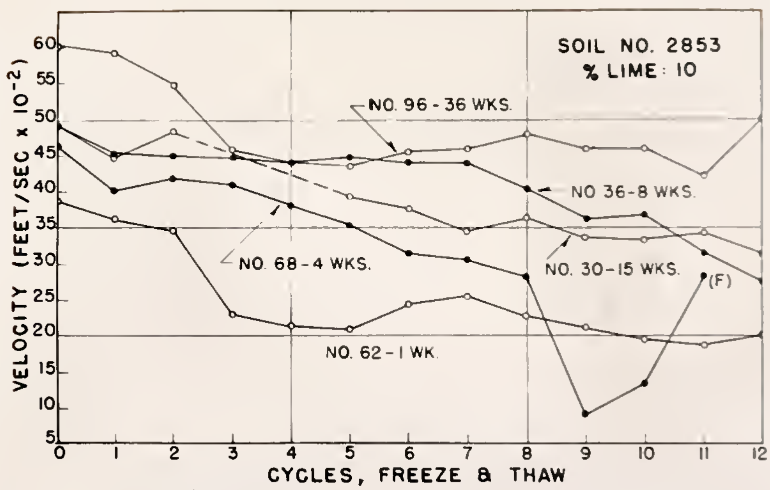
Figure 8 shows the influence upon durability of the percentage of lime mixed with the soil. Specimen 34, containing no lime, failed while being handled at the end of two cycles of freezing and thawing after having lost approximately 36 percent of its original velocity. Specimen 35, made with 5 percent lime, showed a more or less gradual loss in velocity throughout the 12 cycles, its final velocity approximating 54 percent of the original value. The specimen with 10 percent lime, No. 36, showed no appreciable loss in velocity until after seven cycles. From this time on, the velocity fell steadily to a value at the end of 12 cycles equal to 58 percent of the original velocity. It may be observed that Specimens 35 and 36 had essentially the same velocity at the end of the curing period and at the end of 12 cycles of freezing and thawing. It may be important, however, that the time at which the loss in velocity begins to occur was considerably delayed by increasing the lime content of the specimen.

Figure 9 shows the effect of length of curing upon durability. Specimens 62, 68, 30, 36, and 96 were cured 1, 4, 8, 15 and 36 weeks, respectively. After 12 cycles of freezing and thawing their respective



INFLUENCE OF PERCENT ADMIXTURE ON DURABILITY

Figure 8



INFLUENCE OF CURING TIME ON DURABILITY

Figure 9

losses in velocity, based upon their velocities at the end of the curing periods, were 48, 39 (after 11 cycles), 37, 44, and 27 percent. In addition to the comparative loss in velocity during freezing and thawing, attention is called to the actual values of the measured velocities. The specimens cured for 4, 8, and 15 weeks showed a very similar percentage decrease. Generally speaking, however, at the end of any given cycle the specimens with the longer curing periods had the higher velocities. This indicates, in the light of past experiences in testing other materials, that the physical properties of these specimens (modulus of elasticity, strength, etc.) were higher than those of the specimens cured for the lesser time.

Conclusions

Relative to the use of the pulse velocity technique, Whitehurst and Yoder concluded that it was satisfactory for their purpose. Results were reproducible and there appeared to be little operator error. It was believed that changes in velocity are highly indicative of changes in the quality of specimens such as were tested in this study.

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